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CHEMICAL EVIDENCE RELATIVE TO THE ORIGIN OF THE SOLAR SYSTEM *

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Introduction

In 1957 I advanced some suggestions in regard to the origin of the solar system (Urey, 1957). The approach to the problem was not from a fundamental theory for the development of a star with a family of planets based on fundamental principles. An attempt was made to make postulates not in violation of physical principles and in fact supported by such principles which would offer possible and even probable explanations for the evidence recorded in the meteorites and planets. Some of this evidence, and probably the most definite, is of a chemical or physical chemical character. Most of the physical events during the origin of the solar system, e.g., the light, heat, collisions, dissipation of gas, magnetic fields, high energy particles, are gone without a trace, but some bits of evidence remain, many of which are of this chemical or physical character. Among these, an important one seemed to be the presence of diamonds in some of the meteorites, and the course of events postulated the temporary existence of objects large enough to provide the pressure needed to produce diamonds. Gas spheres were postulated on the basis of gravitational instability in a solar nebula, and these supplied a mechanism for producing the required temperature and pressures.

Two papers appeared which bore in an important negative way on these suggestions. Fish, Goles and Anders (1960) proposed that short-lived radioactive elements in small objects of asteroidal size were the source of heat that melted meteoritic materials. This was followed by the discovery of

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Xe^{129} anomalies in meteorites by Reynolds et al. (1963) which seemed to confirm the work of Fish et al. The idea that short-lived radioactive elements, i.e., Al^{26}, were responsible for melting meteorites was an old one of mine but was not developed for reasons that will be presented again in this paper and which still seem valid to me. Again, Lipschutz and Anders (1961) presented reasons for believing that diamonds in meteorites were produced entirely by collisions of meteorites with the earth or during their preterrestrial history, and this paper was followed by the work of De Carli and Jamison (1961) in which diamonds were produced by shock pressures. This work was most impressive and seemed to settle the question. During the years following this work, the interest in the suggestions in regard to the origin of the solar system declined considerably though neither of these two papers disproved the postulates made. They only presented ways of accounting for certain facts in a way that appears to be more acceptable to many people.

What was attempted in the paper of 1957 and in subsequent discussions as well as the present paper is a rather consistent history accounting for many chemical and physical bits of evidence relative to the origin. It is not complete, of course, but it does attempt to avoid postulates inconsistent with other lines of evidence. Solid objects must have accumulated without great loss of certain volatile elements. Melting of these objects again without loss of these elements must have occurred. Probably diamonds must have formed and been destroyed. Certain highly reduced materials occur in the meteorites and some evidence for such materials on the moon exists. The high density elements appear to be more concentrated in the planets than in the sun, and hence the origin of these objects and the moon, which appears to be more nearly of solar composition than the terrestrial planets, are important problems.

PART I. Critical Evidence.

Certain lines of evidence which appear to be critical will be presented and then an outline of some theoretical calculations and a series of events which accounts for these critical bits of evidence follows.

1. Urey (1953) pointed out that certain elements, cadmium, zinc, and particularly mercury, are comparatively volatile, and argued that the earth was not formed at high temperatures since these elements were not highly concentrated in the surface regions of the earth. Also it can be argued that the solid material of the earth and also meteorites was not separated from the solar component of gases at high temperatures, for in this case these elements should have been largely lost which quite certainly is not the case. The material of the earth and meteorites must have been separated from this gaseous fraction at no higher temperature than that of the present earth, and subsequent heating processes must have occurred in such a way that extensive loss of these elements could not occur, e.g., in large masses. Of course, high temperature processes could have occurred but the separation of gases could not have occurred when the solids were at high temperature and finely divided.

2. Diamonds and pseudomorphs of diamonds in meteorites.
The question of the existence of diamonds in meteorites produced by steady pressure and not by shock pressure is important because it enables us to fix pressures and temperatures at some stage of their history. Whether shock-produced diamonds are present is not important for our present purposes. Haidinger and Partsch (1846) and later Brezina (1889) observed cubic forms of graphite in the Magura iron, and Rose (1863,1873) suggested that they were pseudomorphs of diamond. Fletcher (1887) also observed graphitic cubes from Youndegin meteorite and named them cliftonite. Mostly these are cubic in form, but Huntington (1894) found cubo-octahedrons and other forms including

a skeleton octahedron 3/8 inches in dimensions. Cohen and Weinschenk (1891) found cubes and occasional octahedra in Toluca. Farrington (1915) gives a complete review of the older work. Recently, Frondel (1964) has found cliftonite in many irons, and, by etching the metal away, has found masses of cliftonite forms with the cubes lined up over an entire mass of graphite as it occurs in nodules in iron meteorites. He has also found isolated cubo-octahedra. Experienced metallurgists agree that these forms resemble diamonds in appearance, and have expressed the view to this writer that a conservative view is that these objects are pseudomorphs of diamond. It seems most improbable that the original diamonds could have been produced by shock pressures.

Lipschutz and Anders (1964) have suggested that cliftonite is a pseudomorph after Fe_4C which is cubic. However, Frondel finds no iron in cliftonite, and it would be surprising that <u>all</u> the iron would be removed. Also, Fe_4C might be expected to produce Fe_3C (cohenite). Cohenite is found in iron meteorites under such conditions that it appears to have formed under metastable conditions when taenite (face-centered nickel iron) recrystallized as kamacite (body-centered nickel iron). A most unusual series of events must be assumed if cliftonite is a pseudomorph after Fe_4C. This Fe_4C formed, then graphite formed from this without forming Fe_3C which appears to be the stable form above 700°C, even though Fe_3C probably did form metastably below 700°C! Silicon carbide (SiC) is cubic but Frondel finds no silicon in cliftonite, and elementary silicon is not reported in the octahedrites in which cliftonite is found. A considerable expansion when diamond is converted to graphite should occur, but no strains are observed in the metal surrounding the cliftonite. However, the structure of the octahedrites shows that they were originally very large crystals of taenite, since often an entire meteorite shows the symmetry of a large octahedral crystal. Hence all strains could have been removed without difficulty during the formation of such large crystals. The predominantly cubic forms of cliftonite contrasted with the predominantly octahedral forms of diamond is disturbing, but both forms occur in both meteoritic diamonds and cliftonite. The Bushimaie mine of the Congo produces predominantly cubic diamonds and hence both octahedral and cubic terrestrial diamonds are well known.* It is likely that impurities determine the

* I am indebted to Prof. Ramdohr for calling this fact to my attention.

crystalline form of diamond. Generally, octahedral diamonds are more common and probably are the more stable form. It appears that the more unstable cubic forms have been more generally formed and completely destroyed in meteorites.

Diamonds were first reported in the Novo-Urei stone meteorite by Jerofejeff and Latschinoff (1888) and diamonds have been reported in two other ureilites, Goalpara (Urey et al., 1957) and Dyalpur (Lipschutz, 1962). Lipschutz (1964) maintains that these could have been produced by shock pressures. In this case they are of no interest here. Weinschenk (1889) first observed diamonds in the Magura iron. Other discoveries followed. The diamonds are mostly very small and are white or black, and such diamonds are hardly reliably diagnostic with respect to the question of high steady pressures. But small well-formed diamonds have been reported as well, and such diamonds with the characteristic faces of diamonds could hardly have been produced by shock pressures. Thus, Huntington (1894) isolated diamond powder from Canyon Diablo and found some white octahedra. Foote (1891) reports that Koenig isolated a white octahedron about 0.5 mm in size in Canyon Diablo. Moissan (1904) found many finely divided diamonds and some of rounded octahedral forms from a 53 kg sample of Canyon Diablo. Recently, Kennedy and Carter (1964) have polished the diamonds in the Canyon Diablo iron as they are embedded in graphite, and maintains that all the diamonds show from their morphological structure that all were extraterrestrial in origin and were partly destroyed by etching to graphite and were not produced by shock pressures. Moreover, they have found diamonds in a specimen which showed no signs of having been heated to high temperatures by shock effects. Thus several observers of reliable scientific stature without any special reasons for being prejudiced, as is the case for some modern reviewers of the subject, e.g., the present writer, but also others, have reported meteoritic diamonds of such size and crystalline shape that they could hardly have been produced by shock pressures.

What appears to be a reasonable conclusion is that diamonds of sizes less than 1 mm and of good crystalline form and color occur rarely in iron meteorites. Production of such material and its preservation was marginal. The parent of cliftonite, presumably diamond, was produced mostly in small cubic forms though occasionally in octahedra and other forms and was destroyed while some diamonds do remain, so that the destruction was also marginal. This indicates that temperature, pressure and time were barely sufficient to produce and destroy diamonds.

3. Certain meteoritic data.

Much has been written on meteorites and reference is made to Farrington (1915) and Mason (1962) for the general discussion of the subject. In this paper only a few points in regard to the structure and composition which I believe are rather crucial for the problem of the origin of meteorites and the solar system will be discussed. Very little evidence in regard to the physical conditions for meteorite origin exists, simply because the physical events are long past and the physical surroundings of origin are not evident in an object lying on a museum shelf. Hence we should try to conserve what little physical evidence exists and not discard it lightly.

The iron meteorites consist of iron and siderophile elements, i.e., from about 5 to 60 per cent of nickel, some 0.5 - 1.0 per cent of cobalt, and smaller amounts of other elements. The octahedrites are so named because plates of kamacite (body-centered cubic lattice) are arranged on octahedral faces, with taenite (face-centered cubic lattice) between these plates. At one time some of these objects were single large crystals of taenite which slowly cooled with kamacite crystallizing from the taenite. This requires that nickel and iron diffused from one crystal to the other, nickel becoming more enriched in the taenite. Diffusion is slower in the taenite, and nickel-rich borders of the taenite crystals are formed. The entire pattern shows that slow cooling of a metal mass occurred. These features have been discussed by many authors and are well recognized. Uhlig (1954) has discussed this subject and also drawn attention to a difficulty in understanding the structure of the nickel-rich ataxites. If the nickel content of an iron meteorite exceeds about 14 per cent, nucleation of the kamacite in the taenite does not occur, whereas this failure to nucleate is not observed in the laboratory unless the nickel content is greater than about 30 per cent. Uhlig argues that high pressures would lower the temperature at which kamacite separates from taenite with 14 per cent nickel at low pressure, to that temperature at which this separation occurs from taenite with 30 per cent nickel. His estimated pressure is some 50-100 kilobars. Probably nucleation is inhibited by pressure as well as low temperature, and hence much lower pressures than he estimates may be sufficient to produce this effect.

The iron meteorites indicate that very slow cooling occurred and that some undetermind high pressures are required. The Widmanstätten figures were produced in the neighborhood of 300-500°C during times established from millions to hundreds of millions of years (Uhlig, 1954; Urey, 1956). Increased pressures are indicated, but it is difficult to propose conditions that will simultaneously provide the high pressures proposed by Uhlig and the low temperatures ($\sim$300°C) required by the phase diagrams, because the centers of large objects, such as the moon, will not cool from the melting point of iron to low temperatures even in 4.5 billion years.

The iron meteorites have properties indicating that they existed as rather small objects in the parent bodies, and not as parts of large cores of planetary bodies. Henderson and Perry (1958) first called attention to this problem. The surface of Goose Creek meteorite exhibits very deep holes as compared to their diameters, and these are not related to troilite or other nodules in its body. No internal cavities in iron meteorites have ever been reported. Other iron meteorites, e.g., Willamette, have large cavities which might have been produced by turbulent gases during flight through the atmosphere, but this could hardly be true of those of Goose Creek. Henderson and Perry argue that these holes were present before they arrived on earth, and point out that holes of this kind could not be produced by breakup of larger metal masses.*

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* Henderson presented his evidence for the holes in iron meteorites before a group of astronomers, physicists and chemists at Williams Bay in November 1952. N. Nachtrieb suggested that they were due to the usual shrinking of metal as it solidifies and that the peculiar shapes as compared to the terrestrially observed effect were due to low gravitational field. Some 12 years later, I prefer Nachtrieb's explanation to others that have been offered.

If the metal meteorites come from metal masses not greatly larger than the iron meteorites which were formed as liquid masses below the surface of an object such as the moon, it is possible to say something about the melting and solidification process and to suggest the processes which formed the cavities in the iron meteorites. A liquid metal mass, lying on solid silicates, i.e., olivine of higher melting point than iron-nickel, and covered with silicates, which were melted with some solid olivine in contact with the metal, would begin to solidify from the top with some solid metal adhering to the roof and some sinking to the bottom of the mass. The top could be a layer of metal and olivine, i.e., pallasite material. The bottom would not be smooth, but irregular. As cooling from the upper layers progressed, contraction of the metal would occur and cavities would probably form on the bottom layer due to this contraction, just as a depression occurs in the top in a cast ingot of steel or pig iron cooling from the sides. Thus these holes are probably exactly what Dr. Nachtrieb suggested.

Other evidence exists pointing to the same conclusion. Pallasites and possibly some other stone meteorites, which consist of mixtures of silicates and metal in comparable proportions by volume, appear to be boundary regions between metal meteorites and silicate materials, and indeed one specimen of the Brenham Township consists of a typical octahedrite and pallasite joined together.* The prevalance of boundaries of this kind indicates that the metal

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* Anders argues that the Brenham Township shows a distribution of silicate and metal that is not characteristic of silicate floating on top of molten metal but rather of silicate remaining suspended in a silicate melt. The silicate is olivine, and a melted silicate fraction must have been removed, presumably by rising in a gravitational field. Now we cannot have a field to separate the solid silicates from the liquid silicates and then no field in order to keep silicates and metal in suspension!

Suppose a pool of melted iron-nickel were resting on a primitive silicate material and were covered by a silicate mass as assumed in the model above. Melting progressed for a time with melted silicates and solid olivine rising through the metal. Then cooling began from the top, of course. Some chunks of olivine rose in the metal and accumulated in the top of the chamber where solidification of metal began. Then silicates suspended in metal are precisely what would be expected. The writer could propose other models though it is possible to imagine but not convincingly describe possible models on the basis of little evidence.

Fish, Goles and Anders (1960) show that in the case of a static metal core, the silicate reaching the surface in a time, t, should be independent of the radius of the core and hence conclude that the mixture of silicate and metal should be the same fraction of the total for cores of all radii. This conclusion is not correct in the writer's opinion, because convection should occur and this would aid the separation and invalidate their conclusions. Thus, assuming a stationary liquid sphere, more rapid separation of silicates would occur at the surface because of the stronger field. Then a more dense layer would overlay a less dense one in the center and an overturn would occur, bringing silicate to the surface. Of course, a fairly steady convection would be established with silicate accumulating at the surface. Since the less dense liquid silicates have separated from the olivine silicates, we must assume that an effective gravitational field was present, and cannot assume objects so small that the field was too small to produce separation of phases. These processes should result in a comparatively thin zone in which olivine and metal should be mixed as in the pallasites.

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masses were small. These facts have been presented previously (Urey, 1956). Recently, Park et al. (1963) have found a small piece of silicate attached to the Otumpa hexahedrite which does not have a composition of a terrestrial silicate, indicating again that a sample of boundary has been found. These lines of evidence indicate that the metal meteorites come from metal masses which are not much larger than the observed meteorites and are embedded in silicate. Though this conclusion is based on three lines of evidence, one could wish that the evidence were better but there seems to be no evidence for an origin from the core of a planetary object.

Heating by radioactive elements would produce the maximum temperatures at the center of spheres and hence metallic masses would accumulate as a metallic core of considerable size. Hence the evidence for small objects with large surface to volume ratio argues against this origin for heating. This was recognized in 1952 and there appears to be no reason to abandon the argument today.

The chondritic stony meteorites consist in most cases at least of a conglomerate mixture of rounded silicate chondrules, fragments of silicates, and metal particles of both the kamacite and taenite varieties. They are very complex objects. Their chemical compositions vary somewhat, and five or six distinct types are recognized. Two prominent groups on the basis of iron to silicon ratios are known, with ratios of about 0.6 and 0.8 (Urey and Craig, 1953). Definite fractionation of iron relative to silicon has occurred in these objects. Some show evidence for heating after the mixture was made, but most do not, and some show unmistakably that they have not been heated. The elements other than these are about those expected from our studies of elemental abundances, except that indium, thallium, lead and bismuth are much lower than appears reasonable. Iron is much more abundant relative to silicon than is true for the sun, though nickel and cobalt abundances are not badly out of line with solar values. These points will be discussed later. No attempt is made to review models for the origin of these objects. (For a discussion of this, see Urey, 1964).

The achondrites consist of two roughly defined groups which Prior called the calcium-rich and calcium-poor groups. The first has a composition somewhat similar to basalt, and the second has silicon to magnesium ratios more nearly like those of the chondrites. Among the latter are the enstatite achondrites characterized by nearly pure enstatite ($MgSiO_3$). According to recent analyses, some specimens are nearly free of oxidized iron and carbon, and probably this is true of all or nearly all of this group. Table 1 gives Wiik's analysis of Norton County together with the silicate fraction of the enstatite chondrite Indarch, also analyzed by Wiik (1956), the silicate of Monte des Fortes (low iron group) and of Hainaut (high iron group) with all metal, FeS, and FeO eliminated. The analyses of the latter two are remarkably similar. Norton County and Indarch contain no FeO according to Wiik and only small amounts according to recent analyses of Kiel and Fredriksson (1964). At the bottom of the columns are given the amounts of metal, FeO and FeS eliminated from the analyses calculated on the basis of the silicate fraction equal to 100 per cent. Also a mean composition of terrestrial basalts is listed. Basalts are produced by partial melting of the deep rocks of the earth, generally believedto have about the composition of the Monte des Fortes and Hainaut silicates. It is evident that the silicates of Norton County and Indarch were not made by this process. But if the iron of the chondrites were completely reduced and the metal separated, material somewhat like that of Norton County would be secured, and this would be true of other enstatite achondrites on the basis of other analyses, though FeO is reported in some of the older and less reliable analyses. What appears to have occurred is the reduction of iron in a silicate melt from which the metal separated leaving enstatite behind. If crystallization then occurred, some fractionation of CaO, Al_2O_3 and other oxides would occur leaving a somewhat modified silicate behind. Complete melting of the primitive material would be required so that the essential ratio of magnesium to silicon was retained. This indicates that a mass of silicate was heated from above so that complete melting to some depth was attained. The absence or minor presence of carbon and no excess FeO indicates that the reducing agent was not carbon, but a gas, most probably hydrogen. Fig. 1 shows a diagram of the physical situation. Heat from below would produce basalt or something similar to it in magnesium to silicon ratio. If reducing conditions were such that elementary silicon were produced, it would appear in the metallic layer and it is observed in some enstatite chondrites and irons.

But achondrites are known which contain appreciable amounts of iron oxide and yet have high magnesium to silicon ratios. The analyses of two are given in Table 2. These are selected as two more reliable analyses, i.e., they were made in this century and many constituents are reported, indicating care on the part of the analyst. Also, a recently estimated analysis calculated from a solar abundance table due to Prof. H. Suess is given. A marked similarity exists between these compositions. It appears that melting occurred in this case without reduction of iron and without producing basaltic material. Was it heating from above without reduction? But siderophile elements such as nickel and cobalt and others are missing. Then liquid metallic iron and probably iron sulfide trickled through the melt and extracted these elements from the melt, after which it solidified with some separation of CaO and Al_2O_3 from the melt and its concentration in another layer to produce meteorites such as Moore County and LeTeilleul as shown in Table 2. Many unpredictable variations of the process should have occurred.

But we should reconsider the process of heating primordial solar non-volatile matter from above by solar gases. First, as temperatures rose, iron sulfide should melt and flow down into the silicate mass and carry chalcophile elements with it. Then melting of the silicates would occur and iron oxide would be reduced, and metal carrying siderophile elements would sink leaving behind a low density iron-free silicate layer. As the process proceeded two liquid layers might form, a lower density iron-free layer and a higher density layer containing iron oxide resting on a layer of liquid iron which would in turn rest on a silicate layer with iron sulfide below this. Fig. 2 shows the situation diagramatically together with the likely physical processes at the right and the progressive movement of materials at the left.

Solidification would produce further separations, but in a lower gravitational field than that of the earth, such separation may not have been pronounced. Fig. 3 gives a suggestion in regard to possible layers. Again variations in the pattern are most likely and difficult to predict or exclude. Silicon could not be expected to be present in the metal layer since it would react with FeO while passing through the iron-rich layer and it is not found in most irons and other types of meteorites. Apparently both models existed on the same or different planetary objects. It should be noted that the sulfide layer which appears to have been lost may have carried nickel and cobalt which are chalcophile on the earth in the absence of the metallic phase. If this layer were lost, the troublesome low concentrations of these elements relative to iron in the meteorites might be explained. Also the very remarkably low concentrations of In, Tl, Pb, and Bi in most meteorites could be explained by the same circumstance.

In order that diamonds could be produced the process must have occurred under high pressures. Diamonds may have been formed in the metal masses as well as in silicate masses containing carbon just above the metal masses, for example. The ureilites which contain diamonds have chemical compositions which may well have originated in just such a situation. However, Lipschutz (1964) has presented evidence indicating a shock origin for these diamonds.

There are difficulties with this model. Suess' choice of iron abundance is about double that given by Goldberg, Mueller and Aller (1961) and a more recent value given by Aller (1964) for the sun. But iron in Rode and Tatahouine is higher than that calculated from Suess' value and even higher iron percentages may occur in other meteorites. Possibly the primitive solar material may have contained more highly oxidized elements, e.g., trivalent iron, some oxidized sulfur, which would not be in equilibrium with large amounts of hydrogen but still could be present if produced by high energy radiations at low temperature. In this case elemental iron moving from the higher through the lower layer of melted silicate could have been oxidized increasing the iron content of the lower layer. Such possibilities make any estimate of relative proportions quite impossible.

The problem of the concentrations of sodium and potassium in the achondritic meteorites has presented a very puzzling problem ever since the first more reliable analyses became available (Edwards and Urey, 1955, and Edwards, 1955). Reasoning from terrestrial rocks, high sodium and potassium contents are expected in silicates enriched in calcium and aluminum and low alkali contents are expected in silicates low in calcium and aluminum. Generally the achondrites are lower in the alkalis than the chondrites. An exception is Bishopville, an enstatite achondrite, with somewhat more sodium and potassium than the chondrites. The achondrites are erratic with respect to the concentrations of these elements. With the exception of Bishopville, the low calcium achondrites are low in the alkalies. The high calcium achondrites are generally not as high in sodium and potassium as the chondrites but have very variable concentrations. To be consistent with the model proposed here we should conclude that the alkalies are less abundant relative to silicon and other elements than usually supposed, as for example in the Suess-Urey tables. Possibly potassium is less abundant as argued by Wasserburg et al. (1964) and in this case the distributions of sodium and potassium between the calcium-rich and calcium-poor achondrites is understandable even though certain exceptional cases do occur.

4. Composition of the sun, meteorites and planets.

It has been evident for some time that reported densities of the terrestrial planets indicate differences in chemical composition (Urey, 1951). This is true particularly of Mercury, the moon, and the other terrestrial planets. Recent observations confirm the earlier work. Venus, Earth and Mars may agree in composition, but Mercury must have a greater proportion of high density element, presumably iron, and the moon must contain less of such a high density element or a higher proportion of some lower density constituent. Assuming that the meteorites give some valid basis for estimating composition of solid objects in the solar system, we may assume that these variations depend on the relative proportions of iron and silicates. If water were responsible for the low density of the moon, very extensive volcanic activity should have been present because water lowers the melting points of silicates markedly. Such activity on a large scale quite evidently has not occurred. Graphite might be present but the amounts required, namely greater than 10 per cent by weight, are quite out of line with our experience with meteorites and the outer parts of the earth.

The meteorites vary greatly in composition, but if the irons are disregarded because of their great strength and hence greater probability of preservation, the variation of metal to silicate is still considerable, and important fractionation processes have been operative on this material.

Observations on the solar spectrum with the objective of determining its composition have been made for many years, and rather consistent agreement has been secured in recent years. Possibly the most impressive work has been done recently by Aller, O'Mara and Little, with the particular objective of determining whether the iron to silicon ratio could agree with meteoritic values. Using FeI and FeII spectral lines on the one hand and also SiI and SiII lines on the other, they conclude that the iron to silicon ratio is 0.13. This value is not greatly different from previous values and is quite different from chondritic meteorite values which range from about 0.6 to 1.0 with a mean value of about 0.7. Together with the variation in density of the moon and planets, the variation in iron content of the meteorites and the observed iron to silicon ratio in the sun, we may conclude that loss of silicate relative to metal has occurred during the formation of the solar system. Again several lines of evidence lead to the same conclusion. Table 3 summarizes pertinent data in regard to this problem.

One of the troublesome and puzzling points in regard to this conclusion is that nickel, which is not well determined in the sun, and cobalt, which appears to be well known in the sun, are more abundant relative to iron in the sun than in the meteorites. It would be more convenient if this were not true of siderophile elements. Substantial variations in these ratios occur in the meteorites, and a tentative suggestion about this problem will be presented below.

5. The work of Reynolds (1963) on the anomalous abundance of Xe^{129} shows quite definitely that this has been produced from I^{129} and hence that some synthesis of the elements occurred according to his estimates some 30 to 50 million years before degassing of meteoritic material occurred. Reynolds' estimates are not markedly different from those of others. Two views have been expressed as to the origin of this synthesis, namely, during the origin of the solar system due to high energy protons from the sun, or in some high energy process preceding the contraction of the sun. So far as the discussion here is concerned, the latter seems to be the more straightforward postulate, but it may well be that the former can be fitted into the model to be discussed below although the present writer has not been able to do so in any convincing way. Nevertheless it appears necessary to assume times for the evolution of the solar system of the order of 30 to 50 million years.

6. Summary

It seems necessary to assume the following series of events in the order of time as presented.

1. Accumulation of solid materials must have occurred at fairly low temperatures in order to preserve such volatile elements as mercury and others in approximately primitive proportions.

2. High temperatures are required to melt silicates and metals and they must have separated in moderate gravitational fields.

3. High pressures and temperatures were required to produce diamonds followed by lower pressures but still high temperatures to convert the diamonds into graphite pseudomorphs.

4. Slow cooling was required to produce the Widmanstätten figures of the octahedrites. Some pressure is indicated in order to meet Uhlig's observations on the lack of nucleation in the nickel-rich ataxites.

5. Some process is required by which increased concentration of a high density fraction was preserved to produce the planets and meteorites. It is probable that metal objects because of their greater strength were preserved in violent collisional problems.

6. Accumulation of the planets is required.

7. These events must have occupied a time interval of about 50 million years.

In addition, at some point a moon of about solar composition less the gaseous elements was accumulated and captured by the earth or some other origin must be postulated.

PART II

A model for the origin of the solar system.

Students of the problems of solar system origins generally assume that at some time a flat solar nebula lying in the plane of the ecliptic and extending somewhat beyond the orbit of Neptune existed at some early time, say, 4.5 AE ago. This will be assumed in the following discussion.

It seems likely that a contraction of a mass of gas having an angular momentum corresponding to the rotation of gas with the angular velocity of rotation of the galaxy might well leave a disk of primitive composition behind as it contracted. Hoyle (1960) has discussed this problem and assumes that the solar nebula was ejected from the sun after it had contracted to a radius inside that of Mercury due to the effects of magnetic fields. Alfven (1954) also invokes the aid of magnetic fields to solve the angular momentum problem. It does appear reasonable to assume that magnetic fields were instrumental in transferring angular momentum from the sun to a solar nebula and from stars to stellar nebulae generally. However, detailed models cannot be derived from this physical evidence because the magnetic lines of force will be retarded in their rotation at any time that ionized gases are produced at any region of the nebula and in any time sequence. Thus if the nebula were not conducting, no interaction with the magnetic field would occur, and if any part of the nebula at any time became conducting, due to illumination by ionizing radiation from the sun for example, then interaction would occur at that time and region which would result in retardation of the sun's rotation and repulsion of the nebula from the sun. Thus their magnetic interactions are not at all diagnostic with respect to details of the development of the solar nebula, and for this reason they are not considered as critical evidence for this problem. Also, Herbig (1962) points out that T-Tauri stars are losing mass at very rapid rates, i.e., a solar mass per million years and thus the solar nebula may well have been very massive and yet been lost to space by some mechanism which is not understood.

The present author's philosophy in approaching this problem has been determined largely by his experience as a chemist. The chemical elements and their compounds have most complicated and varied properties which cannot be described in terms of manageable theories and they are independent of the wills and arbitrary assumptions of chemists and astrophysicists. The origin of the solar system took place at such temperatures and pressures that these chemical and physical chemical properties of the elements had an importance equal to that of the gravitational field and they cannot be neglected or arbitarily assigned convenient values. This requires that we search for critical evidence for the processes involved and we should recognize that even limited evidence is better than none at all or our most dearly beloved prejudices. In this spirit the lines of evidence outlined above have been accumulated during the last 15 years by the author from data recorded in the literature largely. The following model for events has been developed by trying to accommodate important and critical observational data to reasonable but incomplete physical theory.

LeDoux (1951) first discussed the distribution of mass in a plane layer of gas under its own gravitational field only. The distribution in a direction perpendicular to the plane of the gas is determined by the following equation,

$$\frac{d^2\psi}{dx^2} = -4\pi G\rho, \quad \frac{dp}{dx} = -g\rho, \quad g = -\frac{d\psi}{dx}, \quad p = \rho\frac{RT}{\mu} \qquad (1)$$

The solution of these equations with constant temperature gives

$$\rho = \rho_0 \operatorname{sech}^2 \frac{x}{H}, \quad \text{where } H = \left(\frac{RT}{2\pi G\mu\rho_0}\right)^{\frac{1}{2}} \qquad (2)$$

The potential energy is infinite for each element of volume if the plane is infinite which for the solar nebula is not the case. The distribution of mass in the nebula will be determined largely by the immediate neighborhood, and only the edges of the nebula would require special treatment. Also the virial theorem need not be violated if it is remembered that the disk is finite and hence that the potential energy is finite and the kinetic energy includes the rotation about the sun.

The presence of the sun also affects the problem in two important ways. The entire nebula rotates about the sun with angular velocity varying with distance, and a component of the sun's field perpendicular to the plane should be added to the self gravitational field of the nebula. The latter greatly complicates the mathematical solution and can reasonably be neglected for a massive nebula which will be postulated here.

The problem of rotation of the nebula should be considered. Maxwell concluded that the rings of Saturn were stable and that gravitational instabilities would not develop if the mass in the rings is small. Nielsen (1963) has considered this problem for protons with forces repelling according to an inverse square law, and finds that clustering of ions occurs, but he agrees with Maxwell's finding for attractive forces. Chandrasekhar (1955) has considered the uniform rotation of a three-dimensional gas and concludes that the minimum wavelength for instability in the direction of rotation is the same as that given by Jeans for a stationary three dimensional stationary gas, but that the minimum unstable wavelength in a direction perpendicular to the axis of rotation is

$$\lambda = \left(\frac{\pi\gamma RT}{G\mu\rho}\right)^{\frac{1}{2}} \frac{1}{\left(1 - \frac{\Omega^2}{\mu G \rho}\right)^{\frac{1}{2}}}, \qquad (3)$$

where γ is the ratio of specific heats and Ω is the angular velocity of rotation. If ρ is sufficiently large λ is real, but if $\rho < \frac{\Omega^2}{\mu G}$, the wavelength becomes imaginary, and even for values such that $\frac{\Omega^2}{\mu G\rho}$ is less than but approaches unity, the wavelength becomes very large. It appears to be physically reasonable to assume that the critical mass for the rotating solar nebula would be the mass per unit area of the nebula, which is easily shown to be $2\rho_o H$ multiplied by the square of the wavelength λ , i.e.,

$$m = 2\,\rho_o\left(\frac{RT}{2\pi G\mu\rho_o}\right)^{\frac{1}{2}} \frac{\pi\gamma RT}{G\mu\rho}\;\frac{1}{\left(1 - \frac{\Omega^2}{\mu G\rho}\right)}\quad , \tag{4}$$

or, assuming that the proper value to choose for ρ is $\frac{1}{2}\,\rho_o$,

$$m = 2\left(\frac{RT}{G\mu}\right)^{3/2} \frac{2\pi}{\rho_o}\;\gamma\;\left(1 - \frac{2\Omega^2}{\mu G\rho_o}\right)^{-1} \quad . \tag{5}$$

Adopting this formula, we must next ask what values should be adopted for ρ_o and T. The Roche density (see Jeans, 1929, p.232) gives $\frac{\Omega^2}{2\,\pi G\rho}$ equal to 0.04503, and taking the ρ of this formula as equal to ρ_o, the value of $\frac{2\Omega^2}{uG\rho_o}$ equals 0.181 and the correction term in equation (5) is 1.22. It seems reasonable to assume this value for ρ_o, since tidal effects should disrupt any forming gaseous mass if density were less. In fact, Chandrasekhar's condition for instability is closely related to the Roche density. Using the mass of the sun for determining the value of Ω , i.e., neglecting the mass of the nebula on the Kepler angular velocity, gives

$$\rho_c = \frac{M_\odot}{2\,\pi R^3 \times 0.04503} = \frac{2.1\times10^{-6}}{c^3} \tag{6}$$

where c is the solar distance in astronomical units. It is evident that larger values of ρ would be permissible but we shall use this as the value for ρ_0.*

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* In the first publication covering this work (Urey, 1957), LeDoux' equation for the mass was used and $\rho = 10^{-6}/c^3$ was used for the density following Kuiper. Since then other formulae have been used following Jeans' formula for three dimensional gas. All give comparable values but probably equation (5) is preferable to the others previously used. Uncertainties in our estimates of physical parameters are far more important than small differences in these formulae.

It is difficult to estimate the temperatures. At some time during the contraction of the sun, high temperatures probably obtained at the distances of the terrestrial planets from the sun, but if the volatile elements, e.g., mercury (Hg), are to be retained, provision for the preservation of these elements must be made. A halo of gas and dust of moderate thickness in the plane of the nebula near the sun would effectively shield the nebula from the heat of the sun and hence the nebula might cool to low temperatures. Since ter Haar (1948) and Chandrasekhar had expressed the view that the solar nebula would be turbulent, the writer (Urey, 1957) first tried very low temperatures such that considerable amounts of solid hydrogen would be present in the nebula. It was suggested that this might damp out turbulence. Table 4 is a reproduction of these early calculations in this model. Since fairly large objects are required to produce the high pressures needed for the formation of diamonds, it was suggested that approximately lunar-sized objects, i.e., the mass of the moon plus its solar gases, namely 2.2×10^{28} g, were to be expected. The arguments in regard to diamonds and the ataxite meteorites advanced above again require lunar-sized objects. Using formula (5) and requiring objects of $2.2x10^{28}$ g together with other assumptions made here gives the temperatures listed in Table 5, Column 2, for the temperatures at several distances from the sun. The temperatures required at the distance of Neptune from the sun are unrealistic, and either larger masses must be assumed or higher values of ρ_o must be used to avoid this difficulty. Using Aller's abundances (Aller, 1961), the mass of the moon plus its solar gases is $3.7x10^{28}$ g and the calculated temperatures then are those of the last column of Table 5.

The effects of magnetic fields on the gravitational instability have not been considered, but such effects would be small. The gas of the nebula was considerably less dense than the atmosphere of the earth, but with the densities postulated little ionization would be present except possibly far from the median plane, and the motion of the great mass of gas would be largely unaffected by any magnetic fields that may have been present.

The exact conditions for the gravitational instability cannot be given, but there appears to be no reason for believing that it would not occur provided that a nebula of approximately one-third the mass of the sun or greater were present. No accumulation due to gravitational forces should occur if the nebula had a mass of about one or two per cent of the solar mass as would be expected if the quota of solar gases were added to the masses of the planets and no loss of solid materials from the nebula were postulated.

Such gas spheres should contract as energy is radiated into space; temperatures and pressures on the interior should rise and solids should settle to the center. How rapidly these processes would occur is very difficult to estimate. The radiation rate depends on the opacity for infrared radiation and the rate of settling depends on the size of particles. Some students of meteorites have favored the view that the first solids to condense were micron size and others that these solids were of the size of chondrules, i.e., millimeter sizes. The present writer has been able to bring himself at various times to agree with both these views. If the solids were micron size, settling would be very slow, and if the size of marbles the rate of settling would be much greater. But accumulation of solid objects would occur by these obvious physical processes. So far as the writer is aware, no other physical mechanism has been proposed for this necessary step in meteorite and planetary development.

The pressures and temperatures within gas spheres were investigated by Emden at the turn of this century, but his work was limited to ideal gases. Unfortunately, ideal gases are not applicable to the problem in hand. Bainbridge (1962) undertook calculations for real gases using the best gas equations available and these calculations have been continued by Ostic (1964). Fig. 4 summarizes the calculations of Ostic for central temperatures and pressures as the radius decreases and densities increase. The prominent diagonal line separated the diamond region above from the graphite region below. At higher pressures iron carbide (Fe_3C) should be stable according to thermodynamic calculations. This is not shown in the figure. The curved solid lines show the course of pressures and temperatures as energy is lost and the radius of the sphere decreases for various constant mass objects. The central temperature passes through a maximum at rather low pressures and then fails, and pressure increases, as energy is lost. During the maximum temperature phase, surface melting of the central solid object would occur in the presence of reducing gases. This provides for the history required for the enstatite achondrites and for reduced metal objects of small size below the surface. As Bainbridge showed, the pressures and temperature at the surface of a lunar object at the center of a gas sphere of the masses considered would be approximately the same as those at the center of a gas sphere of the same mass without the presence of the lunar object. The pressures in the outer parts of these solid objects were produced almost entirely by the gases and only in a small degree by the overburden of the solid object. As pressures increase and temperatures fall, solidification of the silicates should occur, and a number of chemical reactions should proceed. Thermodynamic calculations cannot be made with confidence because the fugacities of gases will not be equal to the partial pressures at the high pressures involved, and no good estimates of the fugacities can be made. Approximate calculations indicate that titanium nitride and silicon nitride might be produced at the high pressures and temperatures prevailing at some stages of the contraction of the gas spheres, while the reduction of silica to silicon might occur at some lower pressure stages. More exact calculations covering these points are planned.

Finally, the constant mass lines cross the graphite-diamond stability line. Above this line diamonds should form. It will be seen that the 2.2×10^{28} g line reaches a maximum of 1800°K, hardly sufficient to melt meteoritic silicates and metals, and then crosses the diamond line at 34 kilobars and 1000°K, a temperature at which diamonds would probably not form even in a long period of time. These conditions are very marginal and one would feel more comfortable if the mass were increased somewhat. The line for 3.7×10^{28} g gives more favorable temperatures and pressures. But diamonds in meteorites are small and the cliftonite cubes are small, and all the diamonds were not converted to graphite. In fact, conditions were marginal for these processes as well as the others mentioned above. Also the equations of state of mixtures of hydrogen and helium are not exactly known. Within the limits of these uncertainties the agreement is satisfactory.

At some stage we assume that the dust and gas cloud between these objects and the sun was dissipated and the high atmosphere became warm and hydrogen was lost. Pressures fell as gas was lost and diamonds were converted to graphite. Pressures decreased further and temperatures decreased slowly, and the characteristic features of the iron meteorites developed under the thermal insulation of the overlying silicates.

During this loss of gas it is reasonable to assume that low pressures existed and that the gas was illuminated by the sun. Under these conditions considerable ionization would be present and the gas would be accelerated by magnetic fields moving relative to the gas. Hence angular momentum would be lost by the sun and gained by the gas. Thus the mechanism for loss of angular momentum of the sun postulated by Alfven and Hoyle would apply to this model.

These lunar-sized objects which were called the primary objects do not exist in the solar system at the present time, and if they were once present they must have been destroyed. Collisions appear to be the only mechanism. At the Leningrad symposium on the moon, the author (Urey, 1962) presented approximate calculations which indicate that destruction of such objects by collisions in the region of the terrestrial planets may have occurred during some ten million years. The finely divided silicate materials could have been driven into space leaving larger fragments behind. These should have contained a larger proportion of metallic objects and hence the high densities of the terrestrial objects can be explained.

Finally, accumulation into planets is required. If the gases have been dissipated into space, the total mass in the neighborhood of these terrestrial planets will be small, and following Maxwell's calculations, no accumulation into planets due to gravitational effects should occur, and in fact, it is generally believed that the asteroids are disintegrating into smaller objects. However, if there were present even a few objects large enough to gain in mass when collisions with other objects occurred, then accumulation into planets would occur along lines discussed by Safranov (1954). Probably a lunar-sized object will gain in mass in collision with other objects moving about the sun in neighboring orbits. Thus the presence of lunar-sized objects would have aided the planetary accumulation process and indeed would have been necessary for this to occur at all.

The relationship between the requirements of the observational data and the model for the solar origin are shown in Table 6. It is no accident that they agree because every effort has been made to devise a physically reasonable course of events in order to explain the data. If some of the steps seem extreme, it is well to remember that some puzzling facts exist. Simple models can be secured by ignoring inconvenient data, but is it not true that natural phenomena are mostly more complex than men first imagine them to be? And should we not try to make theories to account for data no matter how troublesome it may be, and then simplify them later if possible?

The Moon

Only after devising the general theory given here did it occur to the writer that the moon was an object of the type described. It is of the correct mass and the correct composition, and if the moon was captured by the earth, it is most improbable that it should be the only such object which existed in the region of the terrestrial planets. There is still disagreement as to whether the moon was captured by the earth or escaped from the earth. It has not been possible to demonstrate that the moon could have escaped, and also no satisfactory mechanism of capture has been proposed.

MacDonald (1964) from his very interesting and thorough study of the recession of the moon due to tidal effects concludes that the moon in its present form should have originated not longer ago than 1.5×10^9 years. Capture at this time is excluded since no reasonable way for its preservation for some 3×10^9 years as a heliocentric object and then its capture by the earth has been proposed by anyone. Escape from the earth 1.5×10^9 years ago is excluded because bombardment by the debris incident to the separation must have covered all lunar evidence of the separation process, since no one ever noted any features of the moon indicative of such a process. Similar collisions of objects with the earth should have occurred at the same time, and it would be most surprising if the effects of such collisions have been completely overlooked by geologists. In fact, it could well be asked as to whether any orderly terrestrial record older than 1.5×10^9 years would be recognizable. MacDonald suggests that the earth had several moons of lower mass before this time which would not move away from the earth and that these collided and formed the present moon some 1.5×10^9 years ago. If so, then the lunar record of this catastrophic event has been covered by debris and again one wonders that no catastrophic record is retained by the earth. Also, the debris can reasonably be supposed to have approximated meteoritic composition and hence increased amounts of siderophile elements should be present in the sediments of 1.5×10^9 years ago. This has not been reported. If the earth captured several moons, would we not expect other planets, particularly Venus, to have several moons or one residual moon also? Also, if we do not know how the earth captured one moon, why is it so certain that it could capture many moons? Still, his postulate indicates that many approximately lunar objects were present early in the history of the system. It seems probable to the present author that the physical properties of the earth and moon may have changed during the recent past, i.e., the last $5x10^8$ years, and thus that the time of $1.5x10^9$ years may not be correct, and in fact that the true time for the origin of the moon is much earlier. Also, the capture process may have been of some kind which is not readily amenable to calculation.

But there is some evidence that the lunar surface composition is at least partly of the highly reduced character required by the theory described here. Kopal et al. (1964) have observed a marked fluorescence in the Kepler region of the moon, and this fluorescence is very similar to that produced when enstatite achondrites are bombarded by energetic protons. It is not possible to identify a substance by such a red fluorescence only, but nevertheless no other naturally occurring material has been found that fluoresces in just the required way, and tentatively this can be accepted as a likely material for some part of the near surface substances of the moon.*

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* Recently, Edward Steele and Celeste Engel have observed that a precambrian dolomite fluoresces strongly in the red under proton bombardment. It would be curious if both highly reduced conditions as shown by the escape of C_2 and highly oxidized materials as indicated by carbonates should exist on the moon.

Kozyrev (1961) observed the spectrum of C_2 in the Alphonsus crater and ascribed this to volcanic action.** It is difficult to understand how C_2

** Some authorities doubt Kozyrev's interpretation. The observed bands deviate in several ways from the Swan bands.

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could be produced in this way. Heating igneous rock containing ferrous oxide to high temperatures would produce carbon monoxide from carbonaceous materials and no gas containing two atoms of carbon has ever been reported from terrestrial volcanic sources. The presence of this spectrum indicates that some subsurface regions of the moon are highly reduced as proposed in the model for lunar origin presented in this paper. The suggestion (Urey, 1961) has been made that calcium carbide (CaC_2) exists below the lunar surface and that water from the interior reacts to give acetylene (C_2H_2) which is decomposed to C_2 by sunlight. (MgC_2 or some other carbides are also possible.) There are several black areas with small craters at their centers in the Alphonsus crater and some other points on the lunar surface. It seems possible that these have been produced by the explosions of acetylene or by reactions of water with carbides at higher temperatures according to reactions such as

$$CaC_2 + 2H_2O = Ca(OH)_2 + 2C + H_2$$

The distribution of these black spots suggests that the distribution of such materials is rather widespread. Also, it may be that graphite has been deposited in the lunar surface regions and that some few collisions with the surface have distributed it about the collision area. It is evident that no such situation exists on the earth at the present time. These lunar facts give some confirmation of the model discussed here, though only chemical investigation of the moon's surface could give conclusive evidence on this point.

It is possible and indeed probable that the smooth gray areas of the moon are finely divided material produced mostly by the great collisions that produced the lunar maria. (Others will disagree with this statement.) This material has been bombarded by smaller objects from the large meteorite-sized objects down to micron-sized particles during the last 4.5×10^9 years. It may be that the larger collisions produced the chondrules as observed in the chondritic meteorites. This process would expose materials in the lunar surface to the solar wind and hence supply a mechanism for the inclusion of inert gases in the lunar surface material. Suess, Wänke and Wlotzka (1964) have suggested that inert gases present in some meteorites were introduced into these objects by bombardment in a solar wind. This could hardly occur if the fragmented solids were in a dispersed condition in space, since such a dust cloud would prevent the acceleration of the ions of the solar wind to high energies. But the surface of an object such as the moon with the surface being stirred by collisions would provide just the conditions required for this solar wind mechanism to be effective. Hunter and Parkin (1961) suggested just such bombardment processes on the moon and predicted the appearance of the lunar surface essentially as observed in the Ranger VII pictures. The chondritic meteorites are very complex conglomerates and possibly the complex series of events to which the lunar surface has been subjected is such that material such as the chondritic meteorites could have been produced. Also, the surfaces of the larger asteroids may well have been subjected to similar processes. However, it is well to consider that asteroids being smaller objects would lose much material in collisions and possibly would never accumulate a substantial layer which had been exposed to the solar wind.

Conclusion

There are many features of meteorites that are not discussed in this paper, such as the structure and composition of the chondrites, and the very interesting rare gases. It is very often the case that hypotheses in regard to these points can be made and many have been made; they are generally contradictory, but to this writer they often appear equally plausible or implausible. Mostly such facts are not diagnostic for problems of origin and evidently are so regarded by the authors themselves, for they refer so casually to various theories of origin, thus acknowledging that various details of almost any model for the origin of the solar system could supply physical and chemical circumstances that would account for these observations. In this paper points that the author has studied for times up to 15 years and which still seem to be valid are used in this discussion. However, it does seem likely that these other data could be accounted for in the general framework of this theory.

The principal competitor in the field discussing the origin of the meteorites is the theory of Fish, Goles and Anders (1960) which tries to devise an origin from objects of the size of the asteroids heated by short-lived radioactive elements, most probably Al^{26}. This paper and subsequent ones have ignored much of the evidence presented in the first part of the present paper, specifically:

1. the variation in density of the planets and moon and the difference in composition of the sun and meteorites and terrestrial planets;
2. the indications that the iron meteorites are fragments of small objects and not cores of planetary objects which must result from internal radioactive heating; and
3. the evidence that some diamonds in meteorites appear to have been made under high steady pressures.

Their theory does not provide a method for the accumulation of planetary objects, either the asteroids or planets, and in fact ignores the fact that the asteroids are disintegrating at the present time.

The object of this paper has not been to review exhaustively all the many papers on meteorites which have appeared during recent years, but to try to bring together in brief form a number of lines of evidence and arguments from different disciplines, and to outline possibly a consistent model for the origin of various features of the meteorites and of the planetary system.

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Table 1

Formulae	Monte des Fortes	Hainaut	Norton County	Indarch	Basalt	Solar System Values (Suess)
SiO_2	54.88	54.76	56.16	61.25	55.59	55.59
MgO	35.39	35.28	42.04	30.37	6.99	34.88
Al_2O_3	4.60	4.68	0.63	2.52	17.99	3.58
CaO	2.53	2.86	0.68	1.65	10.14	2.64
Na_2O	0.99	1.16	0.13	1.75	3.52	1.46
K_2O	0.18	0.22	0.04	0.19	1.72	0.159
Cr_2O_3	0.50	0.45	0.07	0.82		0.70
MnO	0.44	0.43	0.16	0.44	0.35	0.48
TiO_2	0.07	0.15	0.06	0.10	1.54	0.131
P_2O_5	0.41	0.00	0.02	0.89	0.51	0.345
FeO^*	18.23	16.90	0.00	0.00	7.22	14.89
FeS^*	8.47	7.81	1.37	24.67	0.00	---
Metal*	11.12	25.45	0.77	45.23	0.00	---
$Fe_2O_3^*$					6.10	---

Meteorite analyses are by Wiik (1956). Alkalis by the J. Lawrence Smith method are usually somewhat too high.

*These percentages are calculated on the basis that anlyses above the line add up to 100%.

Table 2

Iron-rich Achondrites

	Roda (Ro)	Tatahouine (Chl)	Moore Co. (Eu)	LeTeilleul (Ho)	Solar System
SiO_2	50.38	54.94	48.16	48.14	48.39
MgO	27.10	27.42	8.41	13.93	30.36
FeO	14.91	14.35	15.02	16.71	12.96
Al_2O_3	2.86	0.62	15.57	11.34	3.12
CaO	1.42	0.76	11.08	7.88	2.30
Na_2O	0.38?		0.45	0.22	1.27
K_2O	0.31?		0.09	0.24	0.138
Cr_2O_3	0.64	0.35	0.44	0.53	0.61
MnO	0.22	0.26	0.31	0.22	0.42
TiO_2		0.19	0.32	0.19	0.114
P_2O_5	0.04			0.17	0.300
Fe		0.79			
FeS	1.73	0.35	0.82	0.27	
H_2	0.50	0.14		0.22	

Analyses from those listed by Urey and Craig (1953) were selected as superior because done in this century and many elements were reported.

Table 3

	Mass	Radius	Density	Density $\rho = 0$ $t = 25°C$	Percent Iron
Moon	0.0123	.2728	3.34	3.41	$\sim$10
Mercury	0.0543	0.377	5.59	5.2	$\sim$57
Venus	0.8137	0.957	5.12	$\sim$4.0	$\sim$30
Earth	1	1	5.515		
Mars *	0.1077	0.520	4.22	3.8	$\sim$30
		0.530	3.99	3.6	$\sim$23
Sun (Silicate metal fraction)					$\sim$6
L Chondrites				3.57	22.33
H Chondrites				3.76	28.58

* Dollfus (1962) has remeasured the radius of Mars and secures a value near the larger used in this table. Because of the large flattening of the planet which has not been satisfactorily explained, the radius is still uncertain.

Table 4

Planet	Density (gm/cm^3)	Temperature (°K)	H (cm)	$2\rho_0 H$ (gm/cm^2)	Unstable mass(gm)	Time Years
Mercury	$1.72x10^{-5}$	10.26	$7.4x10^{9}$	$2.6x10^{5}$	$1.1x10^{27}$	$1.3x10^{7}$
Earth	10^{-6}	8.09	$2.7x10^{10}$	$5.5x10^{4}$	$3.2x10^{27}$	$5.9x10^{6}$
Asteroids	$4.6x10^{-8}$	6.53	$1.1x10^{11}$	$1.0x10^{4}$	$1.1x10^{28}$	$2.9x10^{6}$
Jupiter	$7.1x10^{-9}$	5.85	$2.7x10^{11}$	$3.9x10^{3}$	$2.4x10^{28}$	$1.8x10^{6}$
Neptune	$3.7x10^{-11}$	4.55	$3.4x10^{12}$	$2.5x10^{2}$	$2.2x10^{29}$	7×10^{5}
Pluto	$1.6x10^{-11}$	4.44	$5.0x10^{12}$	$1.6x10^{2}$	$3.3x10^{29}$	5×10^{5}

$$2\rho_0 H = 5.5x10^4/cm^{1.59}$$

$$\text{Total mass of nebula} = \frac{2.24x10^{26}}{1.99x10^{33}} \int_{0.3}^{35} 2\rho_0 H 2\pi c . dc \approx 0.35\ M_{\odot}.$$

(It is assumed that the nebula did not extend beyond 35 Å.)

Lunar mass $7.35x10^{25}$gm. Lunar mass plus cosmic gases = $2.2x10^{28}$gm.

Table 5

Temperatures for formation of lunar-sized objects ($m = 2.2x10^{28}$ and $3.7x10^{28}$) at various distances from the sun.

$$\rho_c = \frac{2.1x10^{-6}}{c^3} \quad ,$$

γ = 5/3 except at Mercury where it will be about 1.46 due to the variation in heat capacity of para hydrogen.

Distance of	T°K $m = 2.2x10^{28}$	T°K $m = 3.7x10^{28}$
Mercury	210	296
Earth	88.7	125
Ceres	32	45
Jupiter	17.5	24.7
Neptune	2.95	4.16
Pluto	2.04	2.88

Table 6

History of Meteoritic Matter	Events Postulated
Primordial solar matter Iron probably oxidized and possibly excess oxidation of other elements.	Flat disk of gas and solids of solar composition
	Gravitational breakup into approx. lunar-sized objects, i.e., the primary objects.
High temperatures to melt silicates and metal. Reduction of iron to metal. Heating above a surface & reduction by gas, e.g. H_2.	Solids collect at center of gas spheres at some low temperature
High temperatures and pressures to produce diamonds.	Gas spheres radiate energy, contract and develop high temperatures and pressures on solid body at center of gas sphere. Melting and diamond formation.
Low pressures and high temperatures to produce cliftonite.	Loss of gas. Pressure falls, cliftonite forms. Cooling to form Widmanstätten figures in meteorites.
Slow cooling to produce Widmanstätten figures. Some pressure to produce nickel-rich ataxites.	Breakup of solid objects. Preferential loss of silicates. Accumulation of planets.

FIGURE 1

Gases of solar
composition

Heat

Ca-rich Fe-poor Layer

↓

Enstatite Achondrites

$MgSiO_3$

No FeO

Metal

FeS

Figure 2

Layer	T°K (Estimated)	Hot Reducing Gases			Winds
1	2000°	Highly reduced elements (e.g. Si) produced here Reduction of iron		Low density liquid $MgSiO_3$+other elements No FeO	Circulation
2	1800°	↓ Metal + siderophile ↓ elements		High density liquid MgO, SiO_2, FeO + other elements	Circulation
3	1800°	↑ Basaltic Liquid	↑ Solid Peridotites	Metal + siderophile elements	Circulation
				Silicate melting zone	
	1000°	↓ Liquid FeS + chalcophile elements	↑ Solid Silicates	Silicate + FeS & chalcophile elements	
	Low			Primitive solar non-volatile matter	

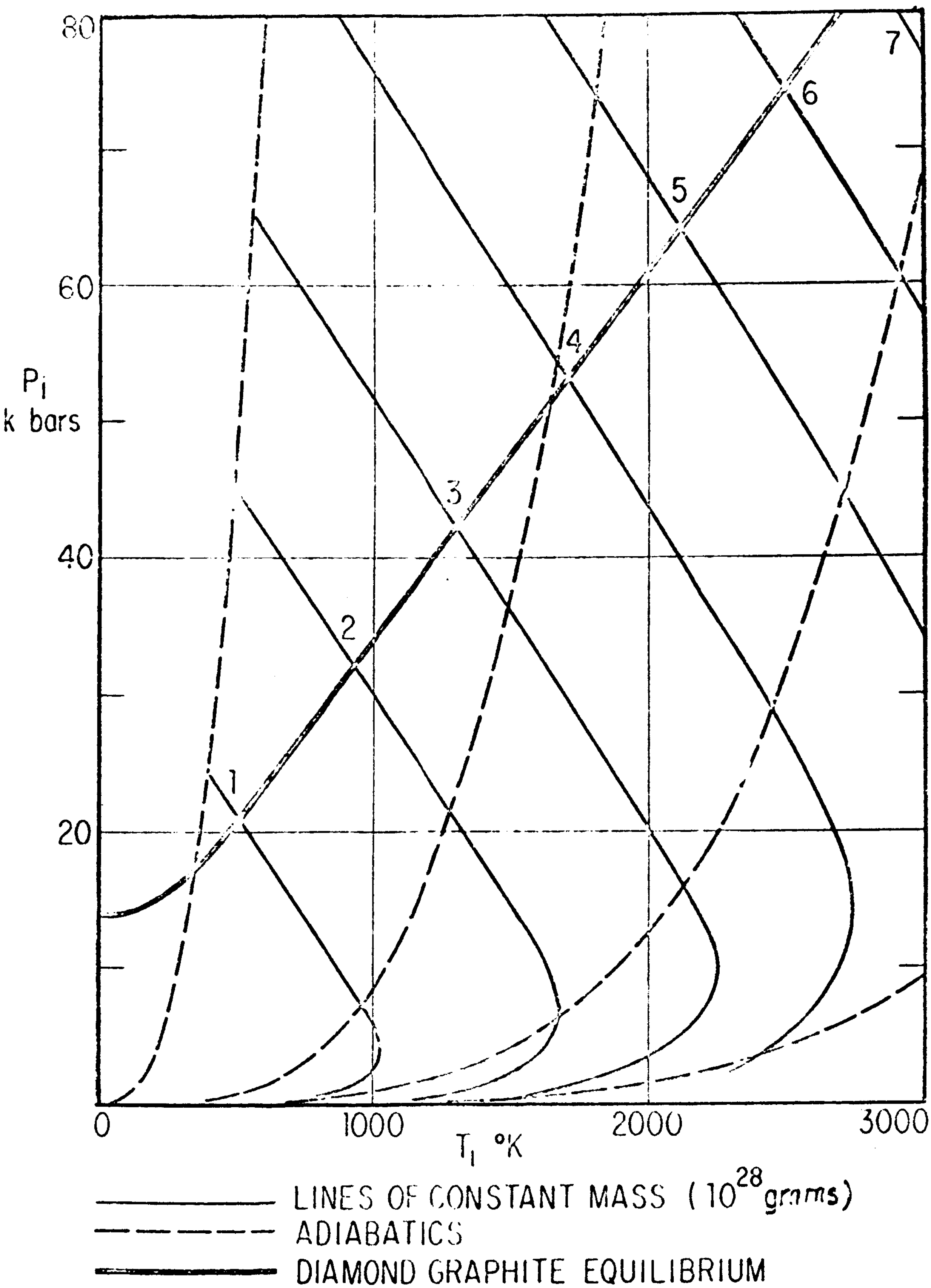
Figure 3

Gases of solar composition

Heat

No. of Layer	Meteorites	Layers
1	None	Ca-rich layer FeO absent
1	Enstatite Achondrites	Ca-poor layer FeO absent
2	Eucrites	Ca-rich layer FeO present
2	Rodites Chladnites	Ca-poor layer FeO present
3	Pallasites	Pallasites
3	Iron	Metal layer
	Lost	FeS layer

FIGURE 4


80
60
40
20
0
P_1
k bars
1
2
3
4
5
6
7
1000
2000
3000
T_1 °K
LINES OF CONSTANT MASS (10^{28} grams)
ADIABATICS
DIAMOND GRAPHITE EQUILIBRIUM